TIGER Reliability Analysis in the DSN

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TIGER is a computer program designed to simulate a system over a period of time to evaluate system reliability and availability. Results can be used in the Deep Space Network for initial spares provisioning and system evaluation. This article describes the TIGER algorithm, the inputs to the program and the output.

I. Introduction

Efficient spares provisioning is a continuing problem in the Deep Space Network (DSN). Correct determination of equipment to be spared, spares stock and optimal network allocation becomes increasingly critical as budgetary restrictions reduce the margin of error. The Deep Space Network Support Section (377) has modified a computer program developed by the Department of the Navy to evaluate system reliability and availability which can aid in this process. Known as TIGER, this program's applications in the DSN include initial spares provisioning, system reliability and availability evaluation and maintenance planning. A major asset is the program's ability to model a wide range of systems. Systems as complex as an entire tracking station to the simplest station subsystem can be accommodated. Models can be simulated on the network, complex, station, system and subsystem level.

Presently the DSN relies on the engineering judgment of the Cognizant Design Engineer and Cognizant Operations Engineer, aided with results from the DSN Efficient Sparing Program, to provision spares for the Deep Space Stations in its tracking network. By taking into account factors such as failure rates, repair rates and shipping time, TIGER can provide the engineers with an analytic tool that takes into consideration all major system parameters.

II. Simulation Theory

TIGER uses Monte Carlo simulation methods to model the system. This procedure assumes a constant failure rate over a period of time for the system equipment. The probability of a failure occurring before time t can therefore be determined by the exponential distribution function $F(t) = 1 - e^{-Lt}$, where L is the failure rate and t is the time to failure (TTF). Substituting the reciprocal of the mean time between failure (MTBF) for L and solving for t, the equation used in the TIGER algorithm is derived: $TTF = -(1/MTBF) \ln [1 - F(t)]$. To obtain an equipment TTF a random number between zero and one is generated and substituted into the equation for $[1 - F(t)]$ (Fig. 1).

Similarly, equipment time to repair (TTR) is simulated by drawing from an exponential distribution with the mean equal to the mean time to repair (MTTR). Here the random number is substituted into the equation $TTR = -(1/MTTR) \ln [1 - F(t)]$ to generate the time of equipment repair.

The system is simulated over a meaningful period of operating time, referred to as a mission. System up and down times are determined by generating a TTF for each lowest replaceable element (LRE) in the system. Initially each LRE is in an upstate. To detect system failure before completion of the operational period simulated, the system is tested as each LRE fails. With each failure a TTR is generated for the LRE and a spare, if available, is put in its place. A new TTF is generated for each LRE experiencing repair to allow further failure after repair. This procedure continues until the mission aborts or the specified mission period is exceeded. The mission is aborted if the specified allowable downtime is exceeded due to lack of a critical equipment or subsystem. A new set of randomly generated values is used to determine equipment TTF and the program is rerun. At the end of each set of 50 mission simulations, reliability and availability figures are computed. Running a large number of missions (typically 500-1000) and averaging the results gives a high degree of accuracy.

TIGER is designed to simulate systems with variations in configuration. The operational sequence simulated is comprised of one or more operational phases. Each phase represents a unique configuration for the system. A maximum of 95 phases of 6 phase types are allowed. The configuration is based on a reliability diagram of the system. The system is divided into as many levels of subsystems as appropriate with the lowest level being that for which the MTBFs and MTTRs are supplied. From a maintenance standpoint this is the LRE.

III. Program Features

Much flexibility is provided by the program. Standby equipment may be designated to come up in the event of equipment failure. Operating rules may also be specified to cause a designated string of equipment to go down if one of the string equipment fails and no spares are available. These rules may vary by phase or remain constant throughout the mission.

Duty cycle, or percent of time used, may also be specified for each LRE by phase. This option is useful in systems where some equipment is used less rigorously than other system equipment. In the DSN this might apply to subsystems that are used less heavily during nontracking periods. Variable MTTRs may also be specified to provide for situations in which an equipment cannot be repaired during a particular mode of operation.

A sophisticated logisitics system is incorporated into TIGER. Numbers and types of spares may be specified as well as at what level the spares will be stocked. Three levels of sparing and associated administrative delay times are provided for. In the DSN this generally corresponds to the station, complex and network levels.

System and subsystem maximum allowable downtimes are user-specified to define mission abort conditions. Both sustained and total downtimes are considered.

User inputs to TIGER are equipment MTBF, MTTR and system configuration. Steps to using the program are as follows:

Define operational period to be simulated and allowable downtime.

Determine subsystem reliability configuration, noting parallel and series equipment.

Determine LREs.

Break system down into subsystems as warranted.

Gather MTBF and MTTR data for LREs

Determine sparing locations and associated logistics delay times.

Determine program options desired

Code input data in TIGER acceptable form.

Run program.

IV. Program Report

In the final report estimators for total system reliability, instantaneous availability, average availability and system readiness are given. In addition, mean uptime, mean downtime and mean time between mission failures are tabulated.

TIGER uses the generally accepted definition of reliability: the probability that the system will perform its intended function for a specified interval under the stated conditions. Mathematically this is calculated by dividing the number of mission aborts by the total number of simulated missions.

Two availability estimators are calculated. The average availability is the probability the system will be in satisfactory operating condition at a random point in time. In the DSN this is functional availability, or the fraction of scheduled service time the system performs its intended function. This is calculated mathematically as:

$$\text{Average Availability} = \frac{\text{uptime}}{\text{calendar time}}$$

The instantaneous availability is the same probability for a specific point in time (i.e., the beginning and the end of the phase.)

System readiness is the probability the system will be in satisfactory operating condition when there is neither a mission abort nor a system failure. The readiness estimator is generally considered the lower bound on the availability estimator.

Most useful from a maintenance standpoint are the individual equipment unreliability and unavailability calculations. This part of the report ranks the equipment in order of contribution to system unreliability and unavailability. This isolates the major contributors to system downtime and calculates the individual equipment percent contribution to unreliability.

Spares usage is reported by LRE. Average spares used per mission and the maximum amount of spares used in a single mission are given. For initial spares provisioning, an unlimited spares stock may be specified. In this case the results would reflect the optimal spares stock for 100% system reliability if it is obtainable with the specified system components.

A more detailed report, if desired, gives a complete listing of system equipment events. Up and down times of all critical LRE are listed in chronological order.

V. Example

To demonstrate the usefulness of the TIGER analysis the program results for the command modulator assembly (CMA) are included. The system has 34 LREs of 13 types. The system consists of two CMAs, one of which must be operational to prevent system downtime (Fig. 2). CMA 801 will come up only upon the failure of CMA 800.

The first part of the report (Fig. 3a,b) lists pertinent system parameters. Two simulation report options are available. The management summary prints a message each time a mission abort occurs (Fig. 4). The phase type, phase sequence, mission number and time of mission abort are listed. The engineering summary is a more complete report that indicates each time an equipment changes status (up to down or down to up) or a phase boundary is crossed (Fig. 5).

After each set of 50 system simulations a "figures of merit summary" is printed. Reliability and availability figures are calculated for each phase of the mission and for the entire mission timeline. The system report (Fig. 6) is for 250 missions.

The equipment failures and corrective maintenance summary (Fig. 7) tabulates for each LRE the number of failures for all missions. The average number of failures per mission and the average number of corrective maintenance hours expended are listed.

The spares report lists the average number of spares used in any single mission. The report for the CMA (Fig. 8) indicates that the spares stock could be more optimally allocated since the entire stock is not used.

The critical equipment list ranks each LRE in order of greatest contribution to system unavailability and unreliability (Figs. 9 and 10). The results for the CMA indicate the subcarrier synthesizer (SC SYN) is a major contributor to both system unavailability and unreliability. Attention should be given to improving the design of the SC SYN to increase the MTBF and to procuring SC SYN spares.

VI. Conclusions

Used in combination with the DSN Efficient Sparing Program, TIGER can potentially aid the cognizant engineers in both initial and ongoing spares provisioning and improve operational availability of system equipment.

The simulation techniques used in TIGER are in wide use today for system reliability and availability evaluation. A second version of TIGER called TIGER/MANNING will soon be completed. This version will include the simulation process of the original program augmented with calculations of optimal worker allocation in system maintenance and repair duties.

The only significant disadvantage, common to all simulations of this type, is the considerable amount of computer time and storage required when a large complex system is modeled. However, most foreseeable applications of this program within the DSN are not on such a scale. Another minor problem is the inevitable random errors found in all system simulations. In actual use the major problem has been a lack of reliable failure data for system equipment. The results, of course, are limited by the accuracy of the parameters supplied.

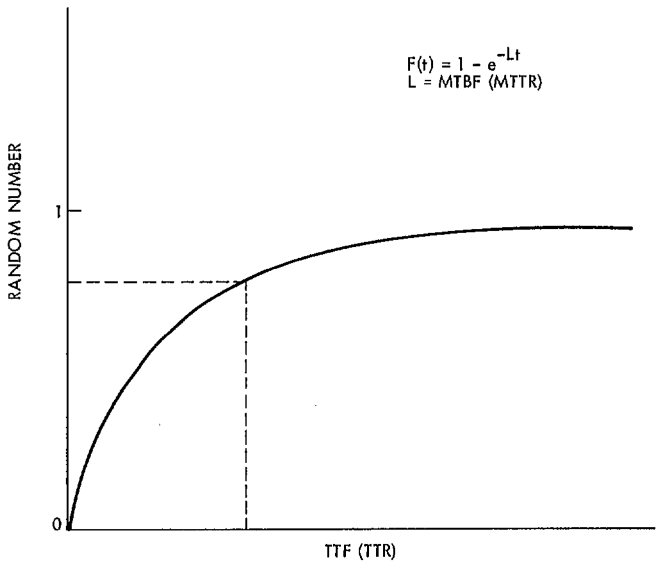

Fig. 1. Generation of time to failure (time to repair) from distribution function

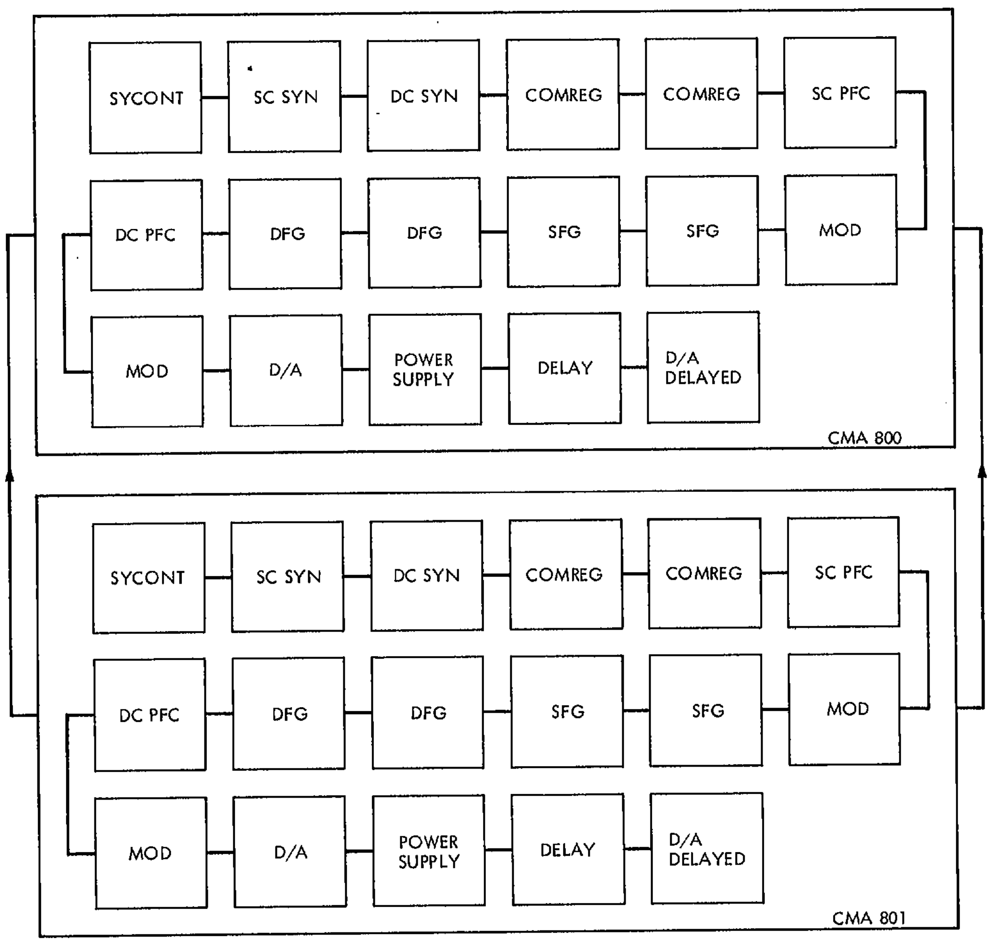

Fig. 2. Command modulator assembly reliability diagram

SIMULATION CONTROL SPECIFICATIONS

STATISTICAL PARAMETERS USED FOR THIS SIMULATION:
250 - MAXIMUM NUMBER OF MISSIONS TO BE RUN
250 - OPTIMUM NUMBER OF MISSIONS TO BE RUN
.998 - SPECIFICATION REQUIREMENT FOR RELIABILITY
1.280 - STANDARD DEVIATION TO BE USED TO CALCULATE LOWER CONFIDENCE LIMIT

985 RANDOM NUMBERS WERE REJECTED PRIOR TO SIMULATION.
SIMULATION BEGINS WITH RANDOM SEED = .94062208

1 PHASE TYPES ARE USED.
1 TIMELINE IS SIMULATED.

PHASE SEQUENCE	TYPE	DURATION	CUMULATIVE TIME
1	1	2184.00	2184.00

PRINTOUT OPTION: MANAGEMENT SUMMARY
REPAIR OPTIONS:
PHASE TYPE 1: REPAIR ALLOWED
100 PERCENT OF REPAIRS ARE PERFORMED ON STATION.

MISSION ALLOWABLE DOWNTIME IS 273.00 HOURS.

MTBF MULTIPLIER = 1.00
MTTR MULTIPLIER = 1.00
BLOCK III CMA

EQUIPMENT CHARACTERISTICS

TYPE	NOMENCLATURE	MTBF	MTTF	DUTY CYCLE	ADMIN DELAY TIME COMPLEX	ADMIN DELAY TIME NETWORK
1	SYCONT	25000.0	2.00	1.00	24.0	336.0
2	SC SYN	12000.0	2.00	1.00	24.0	336.0
3	DC SYN	12000.0	2.00	1.00	24.0	336.0
4	COMREG	25000.0	2.00	1.00	24.0	336.0
5	SC PFC	25000.0	2.00	1.00	24.0	336.0
6	DC PFC	25000.0	2.00	1.00	24.0	336.0
7	DFG	25000.0	2.00	1.00	24.0	336.0
8	SFG	25000.0	2.00	1.00	24.0	336.0
9	MOD	25000.0	2.00	1.00	24.0	336.0
10	D/A	25000.0	4.00	1.00	24.0	336.0
11	POWER SUPPLY	10000.0	2.00	1.00	24.0	336.0
12	DELAY	25000.0	2.00	1.00	24.0	336.0
13	D/A DELAYED	25000.0	4.00	1.00	24.0	336.0

TYPE	EQUIPMENT			
1	1	18		
2	2	19		
3	3	20		
4	4	12	21	29
5	5	22		
6	6	23		
7	7	13	24	30
8	8	14	25	31
9	9	15	26	32
10	10	27		
11	11	28		
12	16	33		
13	17	34		

SPARES COMPLEMENT

SPARES MULTIPLIER = 1.00

TYPE	STATION	COMPLEX	NETWORK
1	0	1	0
2	0	1	0
3	0	1	0
4	0	2	0
5	0	1	0
6	0	1	0
7	3	2	0
8	3	2	2
9	0	2	0
10	0	1	0
11	0	1	0
12	0	1	0
13	0	3	0

BLOCK III CMA

Fig. 3. TIGER Program output: simulation control specifications and equipment characteristics

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                                SIMULATION


MISSION        1 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                 1816.6
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               POWER SUPPLY                 (EQUIPMENT  11) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION        5 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                 1273.9
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               DC PFC                       (EQUIPMENT   6) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION       17 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                 1170.6
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               SC SYN                       (EQUIPMENT   2) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION       24 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                 1550.1
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               SYCONT                       (EQUIPMENT   1) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION       31 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                  759.9
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               DC PFC                       (EQUIPMENT   6) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION       40 ABORTED PHASE SEQ  1 (TYPE 1) AT TIME                     940.4
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               SC SYN                       (EQUIPMENT   2) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
MISSION       49 ABORTED IN PHASE SEQ  1 (TYPE 1) AT TIME                  967.4
BECAUSE CMA EXCEEDED ALLOWABLE DOWNTIME ( 273.0 HRS.) IN MISSION.
               DC SYN                       (EQUIPMENT   3) IS DOWN.
IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
               SC PFC                       (EQUIPMENT  22) IS DOWN.
IT WILL COME UP AT TIME  968.1
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Fig. 4. TIGER Program output: management report

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                                   SIMULATION

START OF MISSION          1********************
  SFG                     (EQUIPMENT  14) FAILED AT TIME             232.1
  SFG                     (EQUIPMENT  14) CAME UP AT TIME            232.9
        SYSTEM WENT DOWN AT TIME  232.1  DOWN TIME IS                     .9 HRS.
  POWER SUPPLY            (EQUIPMENT  28) FAILED AT TIME  548.5
  POWER SUPPLY            (EQUIPMENT TYPE  11) CONSUMED ALL SPARES AT TIME       548.5
  POWER SUPPLY            (EQUIPMENT  28) CAME UP AT TIME            574.7
  MOD                     (EQUIPMENT  32) FAILED AT TIME             968.9
  MOD                     (EQUIPMENT  32) CAME UP AT TIME            995.0
  POWER SUPPLY            (EQUIPMENT  11) FAILED AT TIME            1543.6
  DC SYN                  (EQUIPMENT  20) FAILED AT TIME            1906.4
MISSION ABORTED AT TIME  1816.6
  BECAUSE CMA  EXCEEDED ALLOWABLE DOWNTIME (273.0 HRS.) IN MISSION.
    POWER SUPPLY          (EQUIPMENT  11) IS DOWN.
    IT IS NOT REPAIRABLE DUE TO LACK OF SPARES.
    DC SYN                (EQUIPMENT TYPE  3) CONSUMED ALL SPARES AT TIME       1906.4
    DC SYN                (EQUIPMENT  20) CAME UP AT TIME           1930.6
        SYSTEM WENT DOWN AT TIME 1543.6  DOWN TIME IS               387.0 HRS.
    POWER SUPPLY          (EQUIPMENT  28) WILL FAIL AT TIME         2512.2
    2184.0  END OF SEQ  1 (TYPE 1).
  SYSTEM WAS DOWN FOR  253.4 HRS.  IN PHASE SEQ  1
  AND REMAINED DOWN AT END OF PHASE.
  START OF MISSION        2********************
  DC SYN                  (EQUIPMENT   3) FAILED AT TIME             428.7
  DC SYN                  (EQUIPMENT TYPE  3) CONSUMED ALL SPARES AT TIME        428.7
  DC SYN                  (EQUIPMENT   3) CAME UP AT TIME            454.4
        SYSTEM WENT DOWN AT TIME  428.7  DOWN TIME IS                 25.8 HRS.
  D/A DELAYED             (EQUIPMENT  17) FAILED AT TIME            1157.5
  D/A DELAYED             (EQUIPMENT  17) CAME UP AT TIME           1185.9
        SYSTEM WENT DOWN AT TIME  1157.5  DOWN TIME IS                28.4 HRS.
  SC SYN                  (EQUIPMENT  19) WILL FAIL AT TIME         2629.6
    2184.0 END OF SEQ  1 (TYPE 1).
  START OF MISSION        3********************
  D/A                     (EQUIPMENT  27) FAILED AT TIME            1270.2
  D/A                     (EQUIPMENT TYPE  10) CONSUMED ALL SPARES AT TIME      1270.2
  D/A                     (EQUIPMENT  27) CAME UP AT TIME           1297.4
  D/A                     (EQUIPMENT  27) FAILED AT TIME            2001.9
  COMREG                  (EQUIPMENT   4) FAILED AT TIME            2015.4
  COMREG                  (EQUIPMENT   4) CAME UP AT TIME           2040.9
        SYSTEM WENT DOWN AT TIME  2015.4  DOWN TIME IS                25.6 HRS.
  MOD                     (EQUIPMENT  15) WILL FAIL AT TIME         2206.0
    2184.0 END OF SEQ  1 (TYPE 1).
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Fig. 5. TIGER Program output: engineering report

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FIGURES OF MERIT FOR PHASE SEQUENCE  1 (PHASE TYPE 1):
  BEGINNING:   AVAILABILITY (INSTANTANEOUS) = 1.0000
  IN PHASE:
               RELIABILITY =                    .9240
               AVAILABILITY (AVERAGE) =         .9465
               READINESS =                      .9545
  END OF PHASE: AVAILABILITY (INSTANTANEOUS) =  .8960

FIGURE OF MERIT SUMMARY FOR A GRAND TOTAL OF 250 MISSIONS:

  RELIABILITY              =  .92400          SPECIFICATION     =  .9980
    LOWER CONFIDENCE LIMIT (FOR STANDARD DEVIATION = 1.2800)  =  .9025
  AVAILABILITY (AVERAGE) = .94648
               (INSTANT) = .89600
  READINESS                = .95448
  MEAN TIME BETWEEN MISSION FAILURES (MTBMF) =        27910.6
    LOWER CONFIDENCE LIMIT (90 PERCENT) =             -5101.4 (STD DEV = 1.28)
    VARIANCE =                                    665157560.0
  SYSTEM MEAN UP TIME,  MUT (MTBF ESTIMATOR) =         1288.7
  SYSTEM MEAN DOWN TIME, MDT (MTTR ESTIMATOR) =          21.2
SIMULATION COMPLETE - SPECIFIED OPTIMUM NUMBER OF MISSIONS WERE RUN.
SYSTEM FAILS REQUIREMENT.
  BLOCK III CMA
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Fig. 6. TIGER Program output: system reliability, maintainability and readiness report

EQUIPMENT FAILURES AND CORRECTIVE MAINTENANCE (CM) SUMMARY

NUMBER	EQUIPMENT TYPE	NOMENCLATURE	TOTAL FAILURES	MISSION AVERAGES FAILURES	MISSION AVERAGES CM MANHOURS
1	1	SYCONT	20	.080	.160
2	2	SC SYN	41	.164	.328
3	3	DC SYN	49	.196	.392
4	4	COMREG	25	.100	.200
5	5	SC PFC	22	.088	.176
6	6	DC PFC	21	.084	.168
7	7	DFG	19	.076	.152
8	8	SFG	20	.080	.160
9	9	MOD	15	.060	.120
10	10	D/A	20	.080	.320
11	11	POWER SUPPLY	51	.204	.408
12	4	COMREG	19	.076	.152
13	7	DFG	27	.108	.216
14	8	SFG	17	.068	.136
15	9	MOD	25	.100	.200
16	12	DELAY	17	.068	.136
17	13	D/A DELAYED	12	.048	.192
18	1	SYCONT	23	.092	.184
19	2	SC SYN	50	.200	.400
20	3	DC SYN	40	.160	.320
21	4	COMREG	20	.080	.160
22	5	SC PFC	24	.096	.192
23	6	DC PFC	18	.072	.144
24	7	DFG	13	.052	.104
25	8	SFG	24	.096	.192
26	9	MOD	14	.056	.112
27	10	D/A	20	.080	.320
28	11	POWER SUPPLY	45	.180	.360
29	4	COMREG	22	.088	.176
30	7	DFG	23	.092	.184
31	8	SFG	21	.084	.168
32	9	MOD	24	.096	.192
33	12	DELAY	16	.064	.128
34	13	D/A DELAYED	14	.056	.224
			831	3.324	7.176

BLOCK III CMA

Fig. 7. TIGER Program output: equipment failures and corrective maintenance summary

NUMBER OF SPARES PER MISSION

EQUIPMENT TYPE	EQUIPMENT NOMENCLATURE	STATION STOCK	STATION USAGE MAX	STATION USAGE AVG	COMPLEX STOCK	COMPLEX USAGE MAX	COMPLEX USAGE AVG	NETWORK STOCK	NETWORK USAGE MAX	NETWORK USAGE AVG
1	SYCONT	0	0	.00	1	1	.16	0	0	.00
2	SC SYN	0	0	.00	1	1	.32	0	0	.00
3	DC SYN	0	0	.00	1	1	.32	0	0	.00
4	COMREG	0	0	.00	2	2	.34	0	0	.00
5	SC PFC	0	0	.00	1	1	.17	0	0	.00
6	DC PFC	0	0	.00	1	1	.15	0	0	.00
7	DFG	3	3	.33	2	0	.00	0	0	.00
8	SFG	3	3	.33	2	0	.00	2	0	.00
9	MOD	0	0	.00	2	2	.30	0	0	.00
10	D/A	0	0	.00	1	1	.14	0	0	.00
11	POWER SUPPLY	0	0	.00	1	1	.33	0	0	.00
12	DELAY	0	0	.00	1	1	.13	0	0	.00
13	D/A DELAYED	0	0	.00	3	1	.10	0	0	.00

BLOCK III CMA

Fig. 8. TIGER Program output: number of spares per mission

EQUIPMENT CONTRIBUTIONS TO SYSTEM UNAVAILABILITY

EQUIPMENT NUMBER	TYPE	NOMENCLATURE	DOWNTIME HOURS	UNAVAILABILITY FRACTION	PERCENT CONTRIBUTION
2	2	SC SYN	9181.3	.01682	31.4
11	11	POWER SUPPLY	5521.9	.01011	18.9
6	6	DC PFC	3346.0	.00613	11.5
3	3	DC SYN	2995.1	.00549	10.2
10	10	D/A	2450.6	.00449	8.4
1	1	SYCONT	1714.5	.00314	5.9
5	5	SC PFC	859.3	.00157	2.9
15	9	MOD	720.3	.00132	2.5
4	4	COMREG	636.1	.00116	2.2
12	4	COMREG	501.2	.00092	1.7
16	12	DELAY	397.4	.00073	1.4
9	9	MOD	369.6	.00068	1.3
17	13	D/A DELAYED	334.1	.00061	1.1
13	7	DFG	63.5	.00012	.2
7	7	DFG	47.4	.00009	.2
8	8	SFG	44.8	.00008	.2
14	8	SFG	38.9	.00007	.1

BLOCK III CMA

Fig. 9. TIGER Program output: equipment contributions to system unavailability

EQUIPMENT CONTRIBUTIONS TO SYSTEM UNRELIABILITY

EQUIPMENT NUMBER	TYPE	NOMENCLATURE	NUMBER OF FAILURES	UNRELIABILITY FRACTION	PERCENT CONTRIBUTION
2	2	SC SYN	6	.02400	31.6
11	11	POWER SUPPLY	4	.01600	21.1
1	1	SYCONT	2	.00800	10.5
6	6	DC PFC	2	.00800	10.5
10	10	D/A	2	.00800	10.5
3	3	DC SYN	2	.00800	10.5
5	5	SC PFC	1	.00400	5.3

Fig. 10. TIGER Program output: equipment contributions to system unreliability